

# Diboson-VBF-production in VBFNLO

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INSTITUTE FOR THEORETICAL PHYSICS



- Overview of VBFNLO
- Diboson production via vector-boson fusion
  - scale dependence
  - distributions
  - QCD diboson production
  - interference effects
- BSM extensions
  - anomalous quartic gauge couplings
  - heavy spin-1 and spin-2 resonances

## VBFNLO

- Fully flexible parton-level Monte Carlo for processes with electroweak bosons
  - accurate predictions needed for LHC  
(both signal and background)
  - MC efficient solution for high number of final-state particles  
(decays of electroweak bosons included)
- general cuts and distributions of final-state particles
- various choices for renormalization and factorization scales
- any pdf set available from LHAPDF  
(or hard-wired CTEQ6L1, CT10, MRST2004qed, MSTW2008)
- event files in Les Houches Accord (LHA) or HepMC format (LO only)

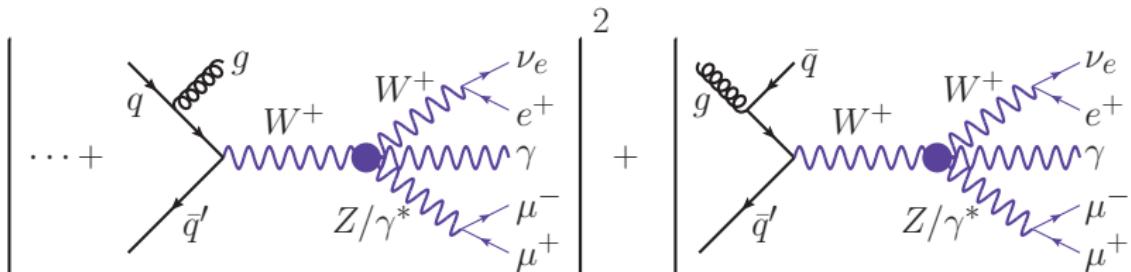
## List of implemented processes

- vector-boson fusion production at NLO QCD of
  - Higgs (+NLO EW, NLO SUSY)
  - Higgs plus third hard jet
  - Higgs plus photon
- } (including Higgs decays)
- vector boson ( $W, Z, \gamma$ )
- two vector bosons ( $W^+W^-$ ,  $W^\pm W^\pm$ ,  $WZ$ ,  $ZZ$ ;  $W\gamma$  in progress)
- diboson production
  - diboson ( $WW, WZ, ZZ, W\gamma, Z\gamma, \gamma\gamma$ ) (NLO QCD)
  - diboson via gluon fusion ( $WW, ZZ, Z\gamma, \gamma\gamma$ )  
(part of NNLO QCD contribution to diboson)
  - diboson ( $WZ, W\gamma$ ) plus hard jet (NLO QCD)
- triboson production
  - triboson (all combinations of  $W, Z, \gamma$ ) (NLO QCD)
  - triboson ( $W\gamma\gamma$ ) plus hard jet (NLO QCD)
- Higgs plus two jets via gluon fusion (one-loop LO)  
(including Higgs decays)

Intermediate state Higgs boson in all processes included where applicable

# Implementation Details

- Helicity amplitude method
- Same building blocks for different Feynman graphs
  - ⇒ Compute only once per phase-space point and reuse ("leptonic tensors")
  - Significantly faster than generated code (up to factor 10)



- Catani-Seymour dipole subtraction scheme

$$\sigma_{\text{NLO}} = \underbrace{\int_{m+1} [d\sigma^R|_{\epsilon=0} - d\sigma^A|_{\epsilon=0}] + \int_m [d\sigma^V + \int_1 d\sigma^A]_{\epsilon=0}}_{\text{real emission}} + \underbrace{\int_m d\sigma^C}_{\text{finite collinear term}}$$

- Photon isolation à la Frixione
  - Processes with real photons in final state can have configurations with photon collinear to final-state quark → QED divergence
  - Simple (e.g.  $R$ ) separation cut between photon and jet not infrared safe
  - Frixione photon isolation

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$$\sum_i E_{T_i} \Theta(\delta - R_{i\gamma}) \leq p_{T_\gamma} \frac{1 - \cos \delta}{1 - \cos \delta_0} \quad (\text{for all } \delta \leq \delta_0 = 0.7)$$

⇒ Efficiently suppresses fragmentation contribution

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# Input and output options

## ■ vbfnl.dat

- process type
- Monte Carlo and beam parameters, masses and coupling constants
- scale choice
  - user-defined constant scale
  - momentum transfer of exchanged W/Z boson
  - $\min(p_T(j_i))$
  - ...
- event file output (LHA or HepMC format)
- histogram output (raw bin data, ROOT, gnuplot, topdrawer)

## ■ cuts.dat

- jet specific cuts ( $p_T(j)$ ,  $R_{jj}$ , parameters for jet-finder, jet veto, ...)
- lepton specific cuts ( $p_T(\ell)_{\min}$ ,  $R_{\ell\ell}$ , ...)
- photon specific cuts ( $p_T(\gamma)_{\min}$ , ...)
- VBF-specific cuts  
 $(\eta_{jj\min}, m_{jj\min}, \text{tagging jets in opposite hemispheres, leptons between tagging jets, } \dots)$

# VBF event topology

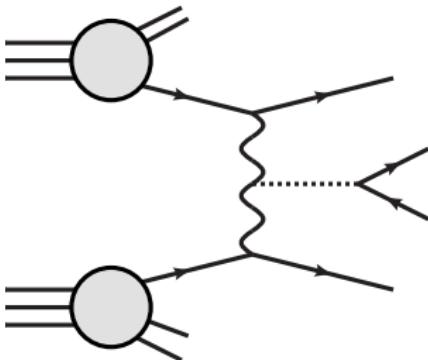
VBF topology shows distinct signature

- two tagging jets in forward region
- reduced jet activity in central region
- leptonic decay products typically between tagging jets

First studied in context of Higgs searches

[Han, Valencia, Willenbrock; Figy, Oleari, Zeppenfeld; ...]

- $\sim 10\%$  compared to main production mode gluon fusion
- NLO QCD corrections moderate ( $\mathcal{O}(\lesssim 10\%)$ )
- NLO EW same size, opposite sign as QCD for  $M_H \sim 126$  GeV  
[Ciccolini et al. , Figy et al. ]
- NNLO QCD known for subsets: no significant contributions  
[Harlander et al. , Bolzoni et al. ]
- advantageous scale choice: momentum transfer  $q^2$  of intermediate vector bosons



# Diboson-VBF production

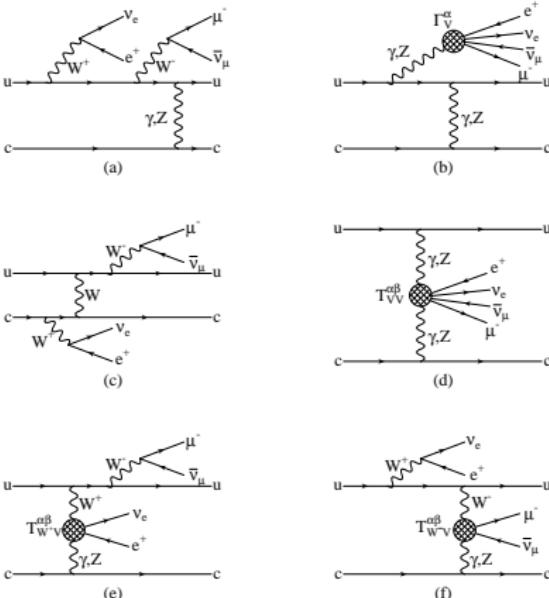
[Bozzi, Jäger, Oleari, Zeppenfeld; hep-ph/0603177, hep-ph/0604200, hep-ph/0701105]

[Denner, Hosekova, Kallweit ( $W^+W^+$ )]

- Part of the NLO wishlist  
[Les Houches 2005]
- background to Higgs searches
- access to anomalous triple and quartic gauge couplings

Implementation:

- modular structure  
→ reuse building blocks
- leptonic decays included
- only t- and u-channel diagrams  
(s-channel implemented separately as triboson process)
- no interference effects from identical leptons



Cuts used in the following:

- Cuts describing general LHC detector capabilities:

$$p_T(j) > 20 \text{ GeV}$$

$$|\eta_j| < 4.5$$

$$p_T(\ell) > 20 \text{ GeV}$$

$$|\eta_\ell| < 2.5$$

$$\Delta R_{j\ell} > 0.4$$

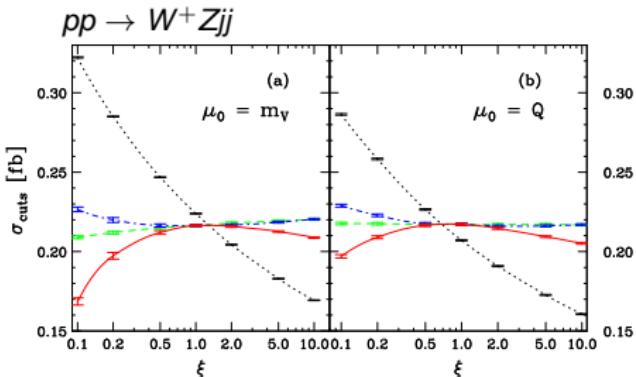
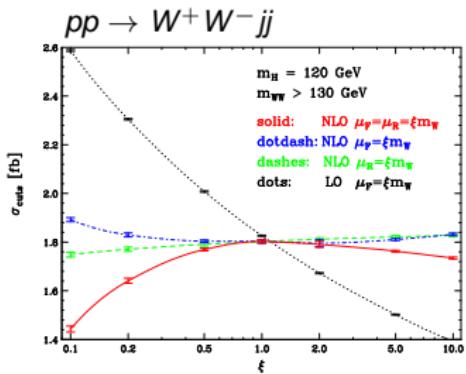
for WZ additionally:  $m_{\ell\ell} > 15 \text{ GeV}$   $\Delta R_{\ell\ell} > 0.2$

- VBF-specific cuts:

- two tagging jets well separated in rapidity  $\Delta y_{jj} = |y_{j_1} - y_{j_2}| > 4$
- two tagging jets in opposite detector hemispheres  $y_{j_1} \times y_{j_2} < 0$
- large invariant mass of the two tagging jets  $m_{jj} > 600 \text{ GeV}$
- final-state leptons between the two tagging jets  $y_{j,\min} < \eta_\ell < y_{j,\max}$

# Scale dependence

Dependence on factorization and renormalization scale

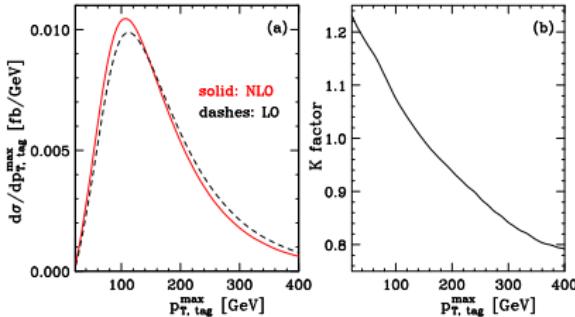


- sizable scale dependence at LO:  $\sim \pm 10\%$
- strongly reduced at NLO:  $\sim \pm 2\%$  (up to 6% in distributions)
- K-factor around 0.98 for  $\mu = m_W$ , 1.04 for  $\mu = Q$  (momentum transfer)

# Distributions

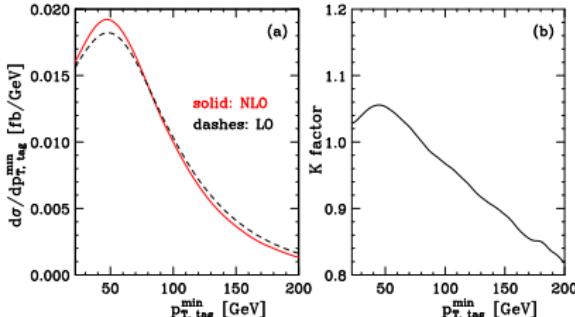
Differential distributions:  $p_T(j)$  ( $W^+ W^-$ )

$p_T$  of the leading tagging jet



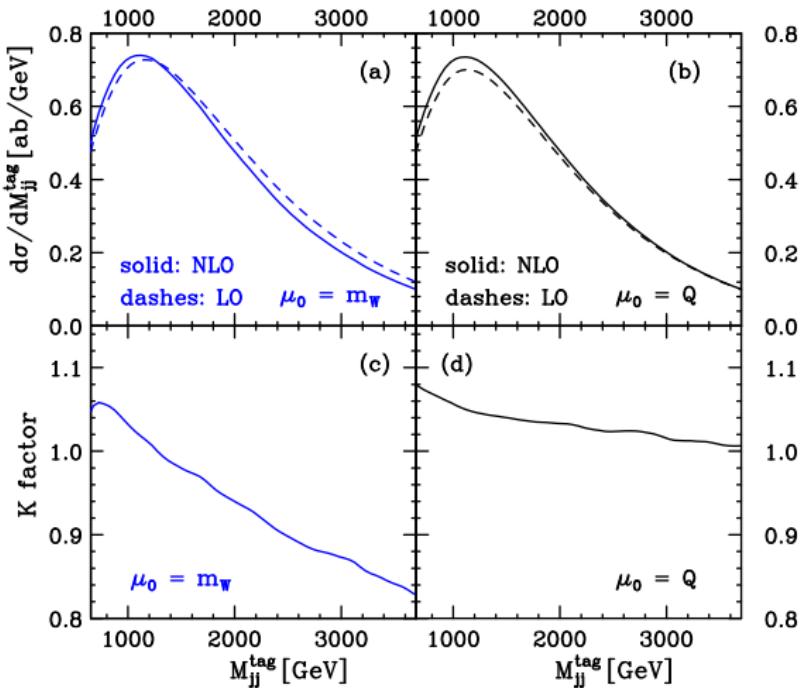
- K factor not constant over range of distribution
- → shape of distributions changes
- → simple rescaling with K factor not sufficient

$p_T$  of the second tagging jet



# Distributions

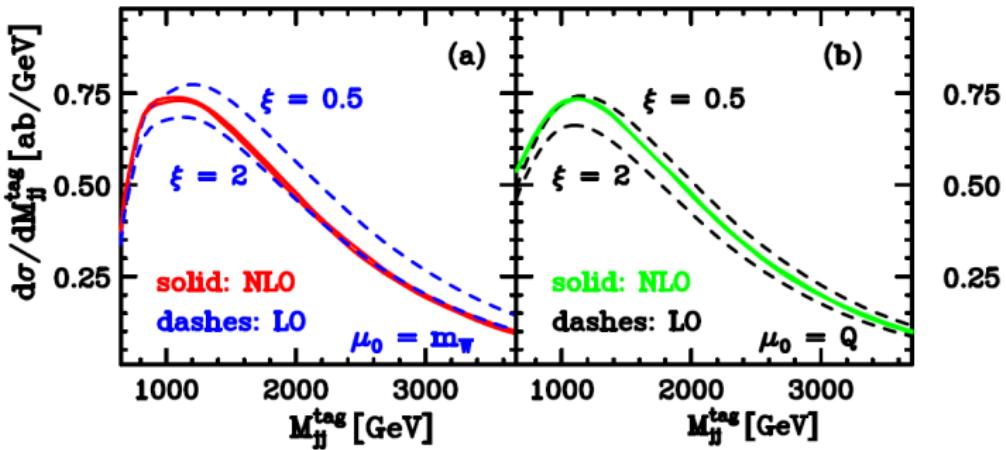
Differential distributions:  $m_{jj}$  ( $W^+ W^+$ )



→ scale choice  $\mu_0 = Q$  leads to flatter differential K factor

# Distributions

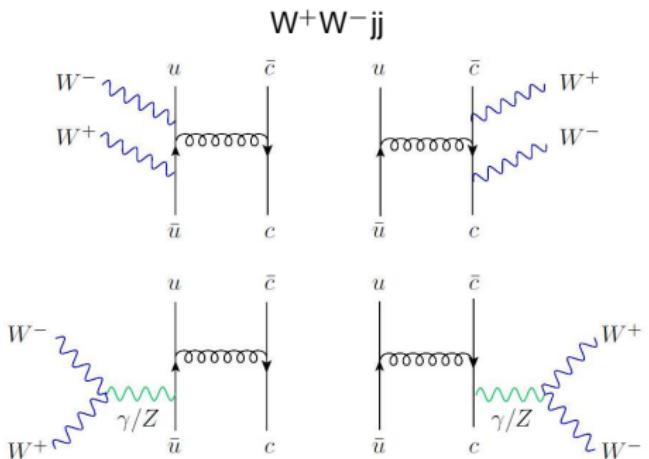
Differential distributions:  $m_{jj}$  ( $W^+ W^+$ )  
scale dependence for LO and NLO distributions



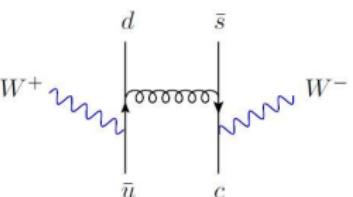
# QCD-Diboson production

So far  $W^+ W^+ jj$  and  $W^+ W^- jj$  known at NLO QCD

[Melia, Melnikov, Röntsch, Zanderighi; Greiner, Heinrich, Mastrolia, Ossola, Reiter, Tramontano]



$W^+ W^- jj \& W^+ W^+ jj$   
(latter after changing quark  
flavors appropriately)

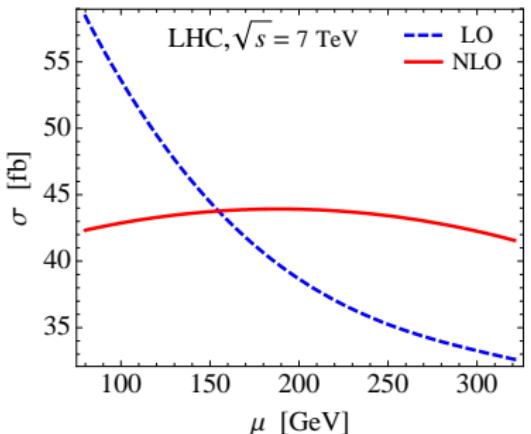


+ diagrams where quark line without attached vector  
bosons is replaced by gluons

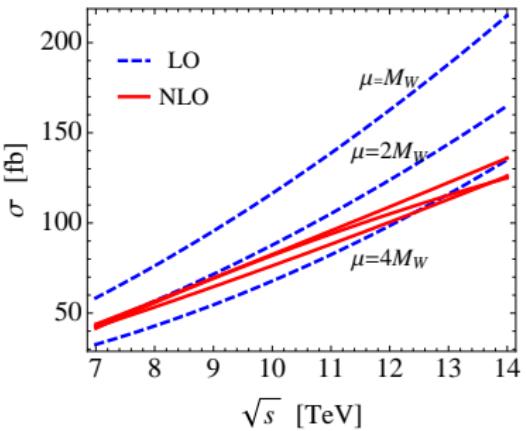
Work in VBFNLO ongoing to implement this process class as well

# QCD-Diboson production

Scale dependence for  $W^+ W^- jj$



Energy dependence for  $W^+ W^- jj$



Scale variation by factor 2 around  $\mu = 2M_W$  ( $\sqrt{s} = 7 \text{ TeV}$ ):

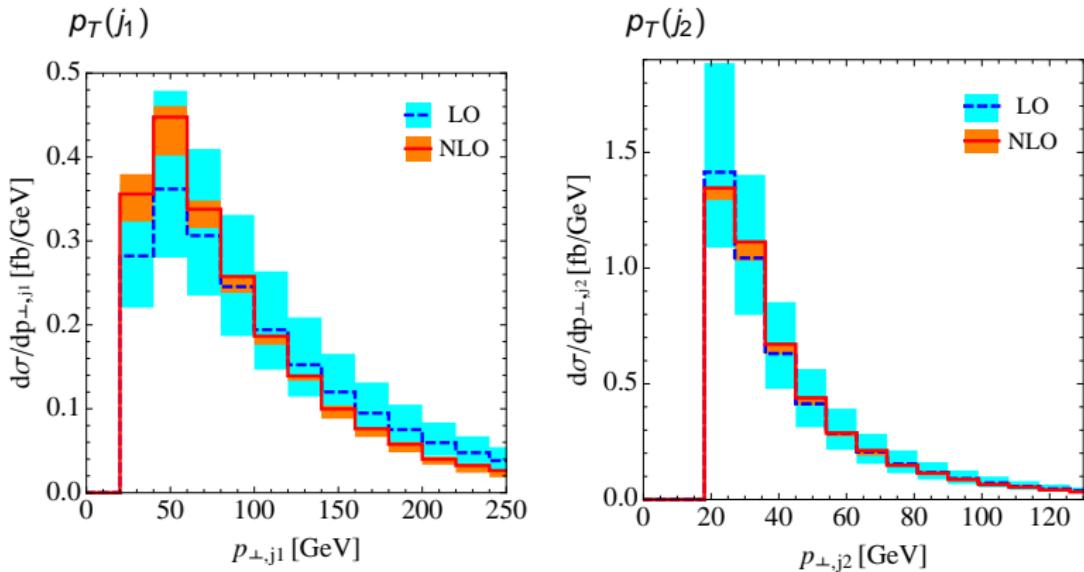
$\sigma_{LO} = 42 \pm 13 \text{ fb}$  (only inclusive cuts, including leptonic decays)

$\sigma_{NLO} = 42 \pm 1 \text{ fb}$

$K = 1.02 \rightarrow$  small (no new processes appearing at NLO)

# Distributions for QCD-Diboson production

Distributions for  $W^+ W^- jj$  ( $\sqrt{s} = 7$  TeV,  $\mu = 2M_W [M_W, 4M_W]$ )



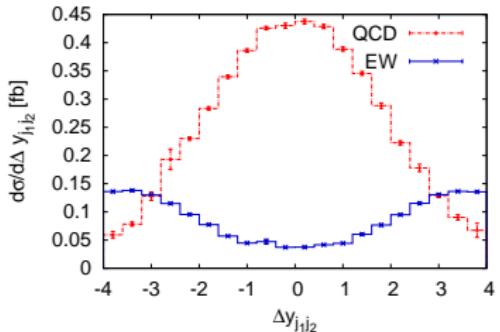
- scale uncertainty strongly reduced
- small change in shapes

# QCD-EW interference

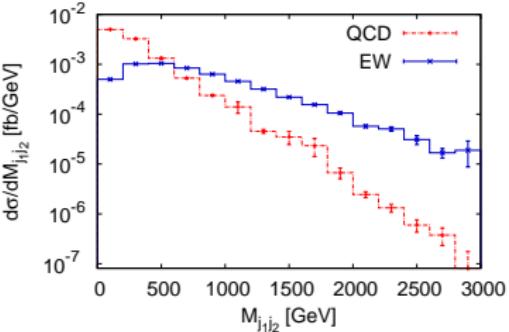
Relative size of QCD and VBF production of  $W^+ W^+ jj$

[Jäger, Zanderighi]

$\Delta y_{j_1 j_2}$



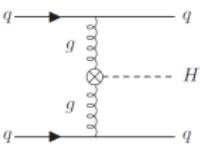
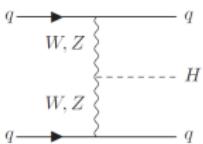
$m_{j_1 j_2}$



$$\begin{aligned}\sigma_{NLO}(\text{QCD}) &= 2.12 \text{ fb} & \xrightarrow{\text{VBF cuts}} & 0.0074 \text{ fb} \\ \sigma_{NLO}(\text{EW}) &= 1.10 \text{ fb} & \xrightarrow{\text{VBF cuts}} & 0.201 \text{ fb}\end{aligned}$$

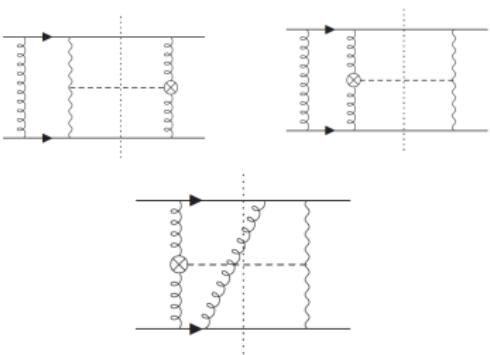
# QCD-EW interference

Interference on diagram level → VBF-Higgs production



Tree-level interference [Georg; Andersen, Smillie]

- neutral current graphs only
- requires same-flavor  $t \leftrightarrow u$  crossing (color trace vanishing otherwise)  
→ large kinematic suppression



Loop-level interference

[Andersen et al. ; Bredenstein, Hagiwara, Jäger]

- neutral current graphs only
- same-channel interference possible (2-gluon exchange in  $|\mathcal{M}|^2$ )
- large cancellation between different flavors

⇒ both contributions completely negligible

# Anomalous quartic gauge couplings

Ideal process to test anomalous quartic gauge couplings

[New in VBFNLO 2.7beta]

Dimension-8 operators in Lagrangian

( $\Phi$  Higgs doublet,  $W^{\mu\nu}/B^{\mu\nu}$ : SU(2)/U(1) field strength tensors):

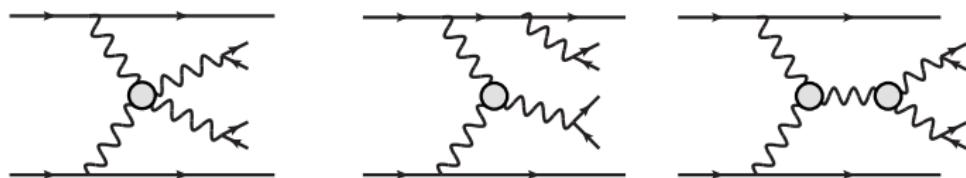
$$\mathcal{L}_{M,2} \propto [B^{\mu\nu} B_{\mu\nu}] \times \left[ (D^\beta \Phi)^\dagger D_\beta \Phi \right]$$

$$\mathcal{L}_{T,1} \propto [W^{\alpha\nu} W_{\mu\beta}] \times \left[ W^{\mu\beta} W_{\alpha\nu} \right]$$

...

(at least) four gauge fields in each term  $\rightarrow$  modify quartic gauge couplings

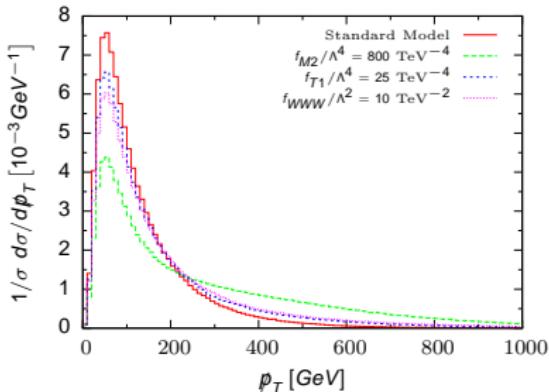
triple gauge couplings contribute as well



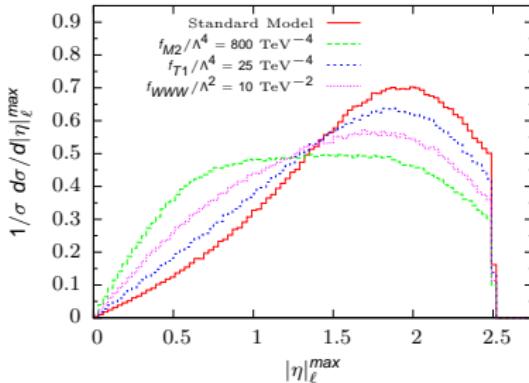
formfactor to avoid unitarity violation

# Anomalous quartic gauge couplings

Normalized  $\phi_t$  distribution



Normalized  $|\eta|_\ell^{\max}$  distribution



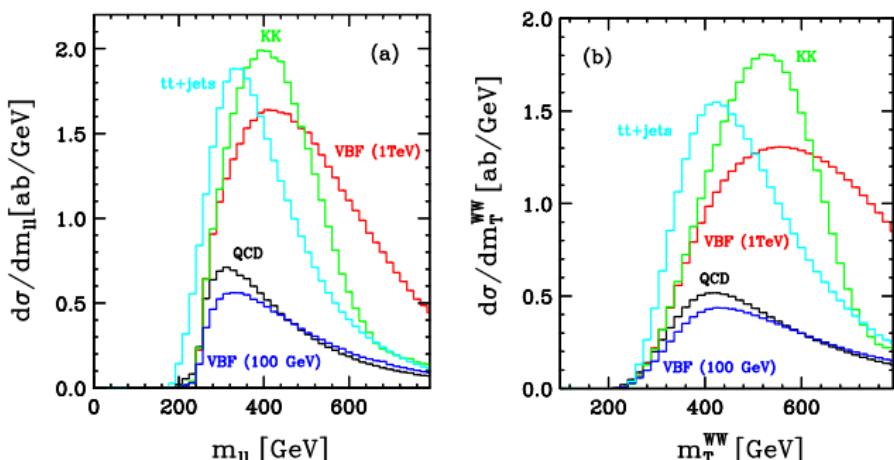
- Anomalous couplings enhance predominantly high-energy region
- $\Delta\sigma \sim \mathcal{O}(1 - 4\%)$  for total cross section,  
 $\Delta\sigma \sim \mathcal{O}(20 - 100\%)$  in high-energy region,  $m_{WW}^T > 800 \text{ GeV}$
- Visible changes in distributions, different for individual couplings
- → distinguish between different couplings

# Heavy resonances in diboson-VBF-production

Warped Higgsless Kaluza-Klein model of narrow spin-1 resonances<sup>1</sup>

[Englert, Jäger, Worek, Zeppenfeld]

- Additional tower of heavy spin-1 resonances  $W_k, Z_k$
- Sum rules between gauge couplings to preserve unitarity
- → Model determined by one parameter: compactification scale  $R$



different scenarios:

- light Higgs  
 $m_H = 100 \text{ GeV}$
- heavy Higgs  
 $m_H = 1000 \text{ GeV}$
- KK model  
 $R = 9.75 \cdot 10^{-9}$

backgrounds:

- $t\bar{t} + \text{jets}$
- QCD WWjj

<sup>1</sup>"Higgsless" part of the model not that useful anymore, but can still give an idea of what to look for

# Heavy Spin-2 resonances

Effective model for interaction of spin-2 singlet with electroweak gauge bosons

[Frank, MR, Zeppenfeld, arXiv:1211.3658]

- Main motivation: Higgs imposter – test against Higgs spin-0 hypothesis
- also studied phenomenology of heavy resonances ( $\mathcal{O}(1 \text{ TeV})$ )
- effective ansatz

$$\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda} T_{\mu\nu} \left( f_1 B^{\alpha\nu} B^\mu{}_\alpha + f_2 W_i^{\alpha\nu} W^{i,\mu}{}_\alpha + 2f_5 (D^\mu \Phi)^\dagger (D^\nu \Phi) \right)$$

- spin-2  $SU(2)$  triplet included similarly
- form factor to preserve unitarity

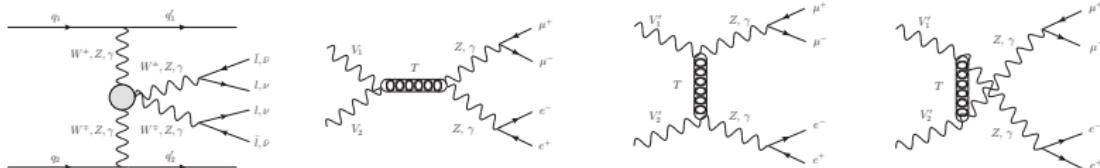
$$f(q_1^2, q_2^2, p_{sp2}^2) = \left( \frac{\Lambda_{ff}^2}{|q_1|^2 + \Lambda_{ff}^2} \cdot \frac{\Lambda_{ff}^2}{|q_2|^2 + \Lambda_{ff}^2} \cdot \frac{\Lambda_{ff}^2}{|p_{sp2}|^2 + \Lambda_{ff}^2} \right)^{n_{ff}}$$

( $q_1, q_2$ : momentum transfer of initial electroweak bosons,  
 $p_{sp2}$ : momentum of spin-2 particle)

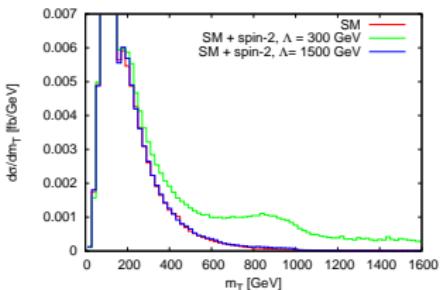
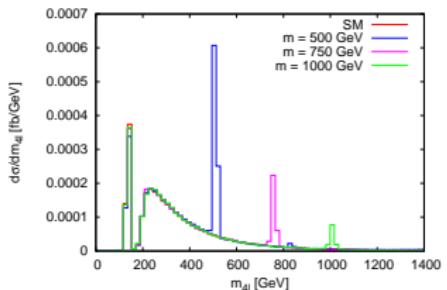
- NLO QCD corrections similar to SM case

# Heavy Spin-2 resonances

## Tree-level diagrams



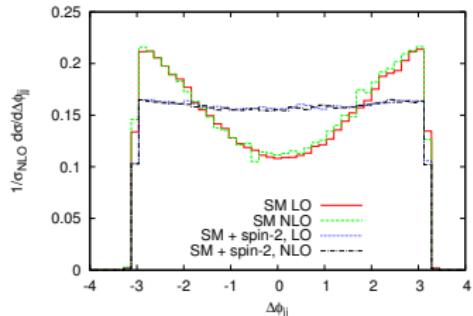
- signal and SM background included
- ZZjj: nicely visible as peaks (depending on width of resonance)  
WWjj: only transverse mass available



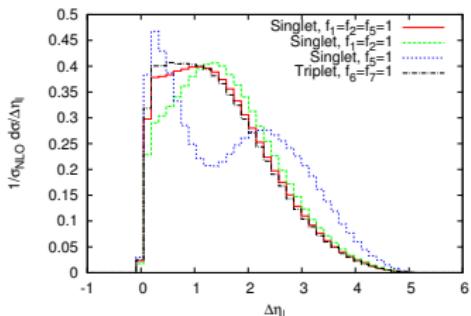
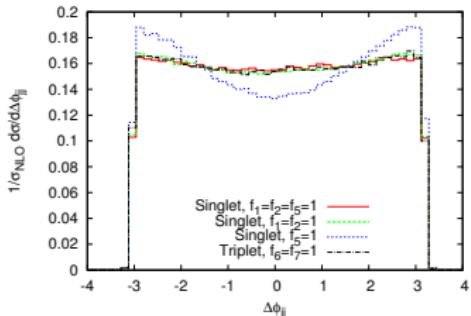
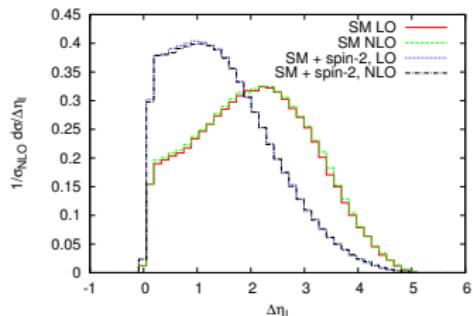
# Heavy Spin-2 resonances

Distinguishing from SM and different parameters (ZZjj)

$\Delta\Phi_{jj}$



$\Delta\eta_{\ell^+\ell^+}$



# Conclusions

- Diboson production via VBF theoretically well behaved
  - K factors small, no huge effects in distributions either
  - small scale uncertainty at NLO QCD
- Diboson-QCD background strongly suppressed by VBF cuts  
interference expected to be negligible
- Ideal process to test anomalous quartic gauge couplings  
and heavy electroweak resonances

VBFNLO is a flexible parton-level Monte Carlo for processes with electro-weak bosons

Code available at

<http://www-itp.particle.uni-karlsruhe.de/~vbfnloweb>

VBFNLO is collaborative effort:

K. Arnold, J. Bellm, G. Bozzi, M. Brieg, F. Campanario, C. Englert, B. Feigl, J. Frank, T. Figy, F. Geyer, N. Greiner, C. Hackstein, V. Hankele, B. Jäger, M. Kerner, G. Klämke, M. Kubocz, C. Oleari, S. Palmer, S. Plätzer, S. Prestel, MR, H. Rzezhak, F. Schissler, O. Schlippert, M. Spannowsky, M. Worek, D. Zeppenfeld

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